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Distributed energy generation and sustainable development

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Abstract

Conventionally, power plants have been large, centralized units. A new trend is developing toward distributed energy generation, which means that energy conversion units are situated close to energy consumers, and large units are substituted by smaller ones. A distributed energy system is an efficient, reliable and environmentally friendly alternative to the traditional energy system. In this article, we will first discuss the definitions of a distributed energy system. Then we will evaluate political, economic, social, and technological dimensions associated with regional energy systems on the basis of the degree of decentralization. Finally, we will deal with the characteristics of a distributed energy system in the context of sustainability. This article concludes that a distributed energy system is a good option with respect to sustainable development.

Keywords: Sustainable development; Reliability; Energy system; Distributed energy generation; Degree of de-centralization

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1. Introduction

Conventionally, power plants have been large, centralized units A new trend is developing toward distributed energy generation, which means that energy conversion units are situated close to energy consumers, and large units are substituted by smaller ones [1]. In the ultimate case, distributed energy generation means that single buildings can be completely self-supporting in terms of electricity, heat, and cooling energy. This principle has already been applied, for example, in hospitals that are very dependent on the reliability of electricity supply [2]. Vehicles are another example of distributed energy generation, but they are not discussed in this article.

The basic idea of distributed energy generation is actually not new. The trend can be regarded as part of a historical continuum. A couple of centuries ago, every single house in the far North was equipped with a furnace. Wooden fuel was collected from the surroundings of the house, since there were no transportation facilities, and traffic conditions were poor. Thus, the functions of the society in general were quite decentralized until the 'first era of decentralization' was ended by the advance of technology and mass production. Today, we live in a network society in the 'Information Age' that is frequently described by the words 'globalization' and 'urbanization'. Social structures tend to be organized around production and consumption [3]. However, the trend is changing. The 'second era of decentralization' can be seen today, but for different reasons [4]. On one hand, decentralization seems to be dictated by threats like the vulnerability of complicated systems. On the other hand, it can be also regarded as 'the world of possibilities', when it comes to 'economic democracy' or the 'redistribution of power'.

A distributed energy system seems to be at its best in large, sparsely settled countries. Hence, countries like Canada or Russia will probably first introduce distributed energy generation. Although, at least a part of present district heating plants will be substituted in the foreseeable future by units producing both heat and electricity. The greatest potential lies in Nordic countries where district heating is an important source of heat. In 2002, 48% of Finland's heating energy was produced by district heating [5]. The proportion of district heating was of a similar magnitude also in other Nordic countries in 2002 [6].

A distributed energy system is an efficient, reliable and environmentally friendly alternative to the traditional energy system. The breakthrough of new solutions often

seems to be simply a matter of decision-making. A positive attitude and a commitment to sustainable development already can be seen both in political definitions and in the opinions of single real estate owners. Readiness to make decisions, however, requires the active promotion of new technology among interest groups, for example, by means of societal embedding [7]. The basic requirement of societal embedding is a thorough understanding about the real essence of new solutions as well as their benefits and drawbacks. A detailed description of the process of societal embedding, is presented by Väyrynen et al. [8].

In this article, we will first discuss the definitions of a distributed energy system. Then we will evaluate political, economic, social, and technological dimensions associated with regional energy systems on the basis of the degree of decentralization. Finally, we will deal with the characteristics of a distributed energy system in the context of sustainability. This article concludes that a distributed energy system is a good option with respect to sustainable development.

2. What is a distributed energy system?

2.1. Traditional definitions

The energy system is an essential part of our society. The concept 'energy system' commonly refers to the energy chain that can be regarded as an entity consisting of energy production, conversion, transmission, distribution, and consumption [9] In this article, political, economic, social and technological dimensions are included in the energy chain. If the aim was only to deal with the technology of the energy chain, the word 'energy infrastructure' would be a more accurate expression [10]. On the other hand, when talking about the energy supply as an issue, the term 'energy generation' can be used.

In the 1900's, energy has been commonly generated in large power plants operating in a central location and transmitted to consumers via transmission and distribution networks. Typical of a centralized energy system (Fig. 1), a large number of consumers are located within a large area. A distributed energy system can be regarded as the opposite of a centralized energy system. The definition, however, is not unambiguous. At least Ackermann et al. [11] and Pepermans et al. [12] have discussed this issue. According to Ackermann et al. [9], the definition should be based on the purpose, the location, the power scale, the power delivery, the technology, the environmental impact, the mode of operation, the ownership, and the penetration of distributed generation. When using this expression, one especially refers to small-scale (under 200 kWe) energy conversion units that are placed in the same location with an energy consumption point and that are used by a small number of people [13,14].

There is still no consensus in the literature about the general terminology of distributed and centralized energy generation. The term 'distributed' seems to be the most common, but the term 'decentralized' is also used, especially in European literature. Although the words 'dispersed' and 'embedded' sometimes can be encountered, they are not frequent. The word 'embedded' is used especially in Anglo-American countries to demonstrate the local use of produced energy [11]. Thus, this term emphasizes the perspective of energy

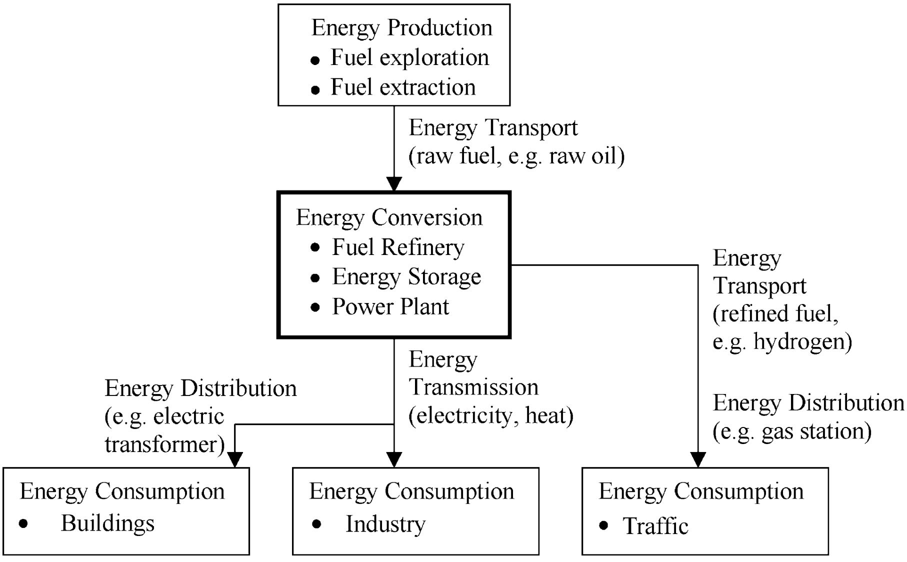

Fig. 1. An example of a centralized energy system.

consumers. Due to their popularity in the literature, we only use the terms centralized, decentralized and distributed in this article.

The terms 'decentralized' and 'distributed' illustrate how single units are integrated into a whole system. To explain the difference between these terms, we use the analogy of energy systems to information systems. According to Palensky [15], decentralized units (in information systems) are autonomous, thus having no interaction with other units. When using these terms, one should remember that all the decentralized systems are distributed, but a distributed system is not necessarily decentralized. Thus, it is reasonable to use the more general word 'distributed' in the context of energy systems. Examples of a distributed energy system and a decentralized energy system are illustrated in Figs. 2 and 3.

Energy consumption is decentralized by nature, although, transmission as well as distribution depend on the location of energy production and conversion units. Hence, the question whether to regard an energy system as centralized, decentralized or distributed, is associated with energy production (the supply of primary energy, e.g. fuels) and energy conversion. Dunn [16] implies that in the future the whole energy chain may be integrated into a building site. In practice this refers to a building that is located in rural areas and has no interconnections to public energy networks. Instead, the building is equipped with solar heating and a solar electricity supply with heat and electricity storage. This is one of the best examples of decentralized energy generation.

On the other hand, a 'virtual power plant' is often presented as a solution for the energy supply within a large area. This means that an energy system consists of a centralized control unit and numerous small local energy conversion units [17]. The control unit receives information about the operational status of the network and determines how to meet the electricity demand at a certain hour. Because every single energy conversion unit

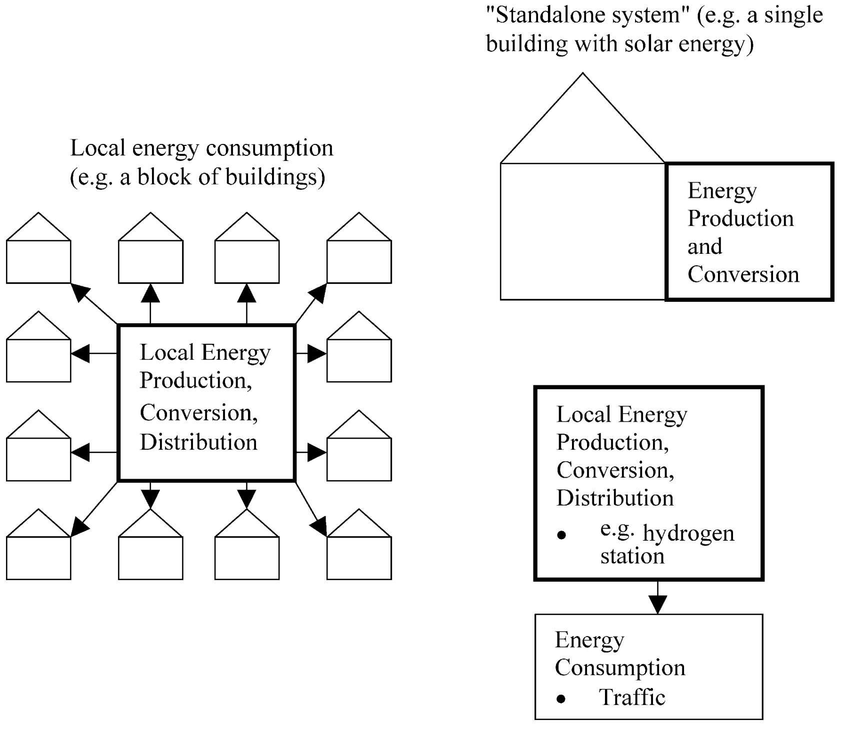

Fig. 2. An example of decentralized energy system.

has a connection to the public electricity grid, bilateral electricity trading becomes possible. This example represents the general case of distributed energy generation.

2.2. The extended definition of a distributed energy system

A great deal of recent research efforts have been made toward the development of technological solutions in the context of energy conversion, fuel support and storage, and the integration of the system. Understanding the link between distributed and centralized energy systems and sustainable development, however, requires more extended consideration in terms of political, economic, social and technological issues. This knowledge is important when developing consulting services for decision support and the implementation and operation of energy systems including new technology. This seems to be an increasing research trend today [18].

The basic question is: What actually can be decentralized in terms of energy systems and how does decentralization affect the system and its operability? Generally, the question is about transferring functions from an upper hierarchy level to a lower one. The Online Source for Public Economics defines decentralization as 'the process of transferring power and resources' [19]. As applied to energy systems, decentralization

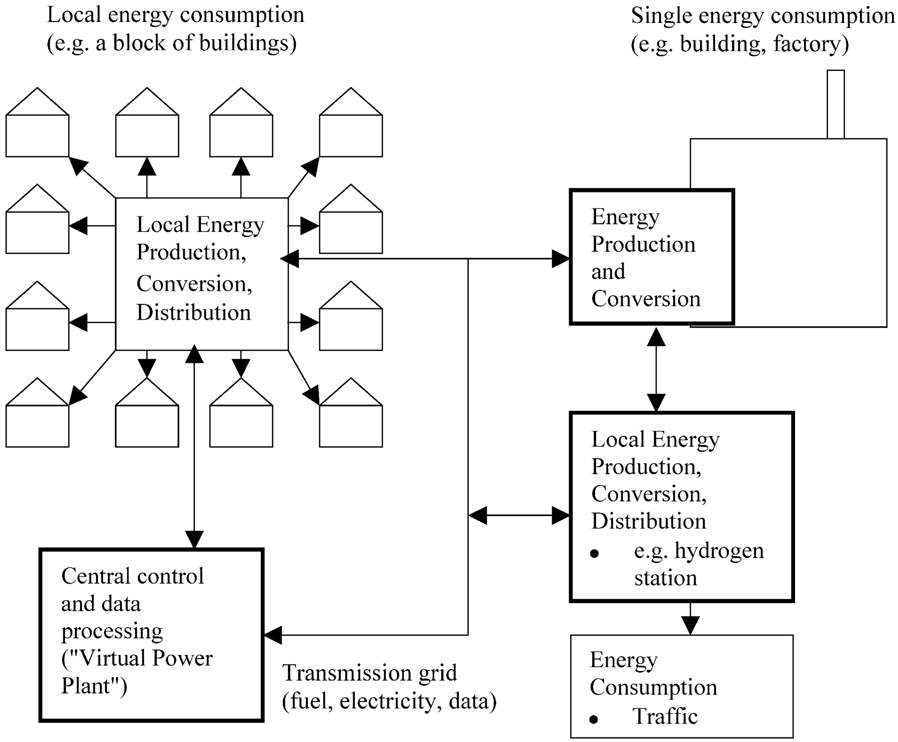

Fig. 3. An example of distributed energy system.

obviously means more than just situating energy conversion units close to energy consumers and substituting large units with smaller ones.

According to the World Bank [20], decentralization includes political, administrative, fiscal, and market aspects. In terms of the political environment, democratization can be seen as a consequence of the decentralization of decision-making. On the other hand, if energy consumers are given the task to make decisions, local responsibility increases with respect to political definitions, laws and rules. Because the number of operators increases in the energy sector, problems may occur with bureaucracy. According to Vartiainen et al. [21], licence procedures of implementation of distributed energy technology can be slow and complicated. Decentralized services for licence application thus could be an interesting subject of research and development, especially in the private sector.

From the economic point of view, the question of *ownership* is of interest in many discussions. The most common opinion seems to be that energy conversion technology should be owned by energy utilities, because they have expertise and other resources to maintain new technology [22]. But is this question really so straightforward? Or is a single energy consumer ready to pay for independence and individuality that is offered by a power plant in his/her own house? In any case, the consequence of decentralization of ownership is also that the financing, incomes and market are decentralized and instead

would be on the shoulders of a few energy utilities. The entrance of numerous small operators into the liberalized energy market would also increase competition.

In terms of social factors, special knowledge and expertise is required when operating and maintaining energy systems. The required number of staff increases when the functions of an energy system are decentralized. Thusly, local employment can be improved by creating new jobs related to distributed energy generation. This, in turn, causes a need for high quality education. Consequently, positive attitudes towards new energy technologies can emerge among educated people. Therefore, as the number of educated people increases, so does the level of support for distributed energy generation.

From the technological point of view, distributed energy generation means local energy conversion. In bold visions, it can be even 'situating energy conversion technology in every cellar', as presented in Vaillant's strategy [23]. The term 'decentralized automation' also has been frequently used in recent studies. Decentralization of control activities of an energy system can be regarded as one of the most important technological aspects in the context of distributed energy generation. Maybe the most referred technological issue in this context, however, is decentralized supply of fuels. Distributed energy generation aims at utilizing local fuels like biomass [24], and establishing local fuel storage. Although the amount of technology in a system principally increases due to decentralization, we emphasize that the vulnerability of the whole system decreases.

2.3. The degree of decentralization

We can hardly imagine a situation where the total electricity consumption of a country is covered by a single power plant On the other hand, the return to complete self-sufficiency in terms of energy seems to be unlikely. The energy system is thus hardly going to be completely centralized or completely decentralized. It is probably going to be somewhere in between, creating a system where centralized and decentralized sub-systems operating parallel to each other.

Changes in the operational environment are slow [5]. Hence, the more decentralized subsystems that already exist in an energy system, the more suitable that energy system probably is for the further development of distributed energy generation. If the most favorable regions can be recognized in this respect, energy utilities and product suppliers will become aware of the best market opportunities for distributed energy technology.

Different types of regions can be distinguished by means of political, economic, social, and technological parameters that indicate if the energy system is completely centralized or decentralized or somewhere in between. This analysis can also be applied when evaluating the vulnerability of an energy system. This approach has been used previously, for example, when building scenarios for a gradual transition to an energy system applying new technology [25]. It also provides a definition for distributed energy generation.

The parameters (indicators) should be easily measurable and comparable. Therefore, the analysis should be carried out separately for both electricity and heating (or cooling) energy chains. In this context, a region is apparently best represented by the regional averages of indicators. Assume an energy system (energy chain) consists of 'units' and 'consumption nodes'. The units can be technological units like power plants or fuel extraction sites, political units like bureaus, economic units like banks, or other units like

private decision-makers. A 'consumption node' is represented by a single building or a grid interface. The most unambiguous indicator of decentralization is the number of 'consumption nodes' per number of 'units'. In other words, this indicator illustrates how many 'consumption nodes' are served by a 'unit'. Other suitable indicators could be, for example, the number of units per area of a region, unit size, or the distance between a unit and a consumption node.

When concerning the decentralization of economic, political, and social 'subsystems' in the context of energy chains, the interaction between consumption nodes should be defined, for example, as the number of negotiations concerning the energy supply of a region. Accordingly, the use of local resources should be illustrated as per the proportion of the local power plant capacity to the total power plant capacity used to satisfy the local energy needs. The local and global numbers of alternative (energy) deliverers (and fuels) describe the state of the region with respect to the decentralized market. This information is usually difficult to achieve because of the lack of statistics and because of the ambiguous nature of these indicators.

In this article, the 'degree of decentralization' means a set of conclusions that can be made on the basis of the previously mentioned indicators. Thus, it does not have a mathematical expression. The more decentralized an energy system is in a certain region, the

- smaller the number of consumption nodes per number of units
- larger the number of units in that region
- smaller the unit size
- smaller the average distance between a unit and a consumption node
- slighter the interaction between units (and consumption nodes)
- more diverse the use of local resources
- greater the number of deliverers (and alternative fuels) on the market

In principle, this approach can be applied to any region varying from a single energy consumer to the whole world. Because the variables are statistical, they commonly vary from one year to another. Consequently, the degree of decentralization depends on both time and location. In addition, it depends on the point of view of the observer. For example, a district heating system can be regarded as 'very decentralized' when considered from the point of view of a whole country. On the other hand, it probably seems to be 'quite centralized' when the observer is a single energy consumer.

Let us demonstrate this analysis with some numbers. The question whether an energy system is decentralized or centralized, commonly refers to the decentralization of energy conversion technology. Consequently, a good idea about the degree of decentralization can be achieved on the basis of the technological indicator the 'number of consumption nodes per number of units'. If there is unity in each energy conversion unit in the energy chain, then the energy system is unambiguously decentralized with respect to energy conversion technology. In the context of large regions (e.g. a country), however, an energy system can be regarded as decentralized if a unit serves dozens or even hundreds of consumption nodes.

The regional average size of power plants is another applicable technological indicator when evaluating the degree of decentralization. If the average power plant size is less than 2 MWe, the system can be considered decentralized when talking about the energy

Table 1
The average size of power plants referring to centralized and decentralized energy generation in terms of different regions

Region	Decentralized	Centralized
Country	<2 MWe	>1000 MWe
Territory	<250 kWe	>100 MWe
Municipality/City/Town	<100 kWe	>2 MWe
Village/Group of houses	<25 kWe	>100 kWe
Residential building	1–5 kWe	>25 kWe

generation at the level of a whole country. If the size is less than 100–250 kWe, the term 'small-scale' energy generation is used [5,11]. If the total electricity consumption of a region is covered by a single power plant, then the energy generation is unambiguously centralized. In the context of large regions (e.g. a country), an energy system can be regarded as centralized if the average size of power plants is 1000 MWe. Table 1 presents boundary values that distinguish between power plant sizes referring to a centralized or decentralized energy system, depending on different regional perspectives.

2.4. A study on the degree of decentralization in Finland and Sweden

This section presents a simple example to illustrate the degree of decentralization in a practical case. Consider the supply of electricity in Finland and Sweden. Only technological indicators and 'official' power plants are concerned. 'Unofficial' power plants like private-owned generators and solar panels have not been included because of their slight importance in the national energy supply at the moment. On the other hand, statistics are difficult to obtain for 'unofficial' power plants.

Assume the number of consumption nodes is the same as the number of buildings in both Finland and Sweden. Because these countries do not have domestic fossil fuels, primary energy supply is concerned with respect to peat production. This is reasonable, because peat is one of the most important domestic fuels in Scandinavia, and because the number of peat harvesting areas has been recorded. The capacity of domestic power plants is estimated to be the same as the most recent annual national peak power demand. The cases representing completely decentralized and centralized energy systems, are established using reference values based on present conditions in the Finnish energy system. One should remember that there is not just one single correct way to define the degree of decentralization. This example can be regarded as a subjective opinion of the authors of this article. In order to obtain a reliable picture of the degree of decentralization, however, one should be assured of the comparability of reference cases.

The reference cases have been established on the basis of the following assumptions:

- all the energy that is produced in a country is consumed in the domestic market
- the proportion of domestic primary energy resources is 50% in the decentralized case and 1% in the centralized case
- there are 10 peat harvesting sites in a country in the centralized case
- the need of additional capacity can be satisfied by increasing the number of harvesting sites

– the capacity of a harvesting site is 14,000 m^3 per year in the decentralized case, and the capacity per site area is like in the Finnish case in 2002
– the proportion of domestic electricity is 100% in the decentralized case and 50% in the centralized case
– the average size of a power plant is 2 MW in the decentralized case and 1000 MW in the centralized case
– there is no need for a high voltage (220–400 kV) transmission network in the decentralized case
– all the electricity is conducted through power stations
– one power plant is served by one power station

The overall comparison between Sweden, Finland, and the reference cases is presented in Table 2. The information is based on statistics for the year 2002 [26–32]. (Fig. 4) The degree

Table 2
Indicators for evaluating the energy system in Finland, Sweden, and the reference cases [26–32]

Indicator	Finland	Sweden	Decentralized	Centralized
Basic information				
Area of the country [km^2]	338,145	449,964	338,145	338,145
Total annual electricity consumption [TWh]	84	163	84	84
Peak load [MWe]	14,000	18,000	14,000	14,000
Total number of consumption nodes	1,330,410	2,870,545	1,330,410	1,330,410
Supply of primary energy (domestic)				
Number of sources[a]	300	203	10,200	10
Total capacity of all the sources [m^3/a]	20,000,000	2,885,000	142,857,143	2,857,143
Total area of all the sources [ha]	37,000	43,561	264,286	5286
Area served by one source [km^2]	1127	2216	33	33,815
Number of cons. nodes/source	4435	14,140	130	133,000
Average area of a source [ha]	120	214	26	529
Capacity of a source [m^3/a]	67,000	14,200	14,000	285,714
Capacity of a source/area [m^3/ha, a]	540	66	540	540
Proportion of domestic primary energy [%]	7	2[b]	50	1
Supply of secondary energy (domestic)				
Number of electric power plants	419	147	7000	7
Area served by one power plant [km^2]	807	3060	50	48,306
Number of cons. nodes/power plant	3175	19,137	190	190,059
Average size [MWe]	33	122	2	1000
Proportion of domestic electricity [%]	86	80[b]	100	50
Transmission				
Total length of transmission lines [km]	6400	15,000	0	15,000
Distribution				
Total length of distribution lines [km]	7600	15,000[b]	5000	15,000
Number of power stations	100	150	7000	7
Area served by one power station [km^2]	3381	3000	48	48,306
Number of cons. nodes/power station	13,304	19,137	190	190,059

[a] In this example: a peat harvesting site.
[b] An estimate.

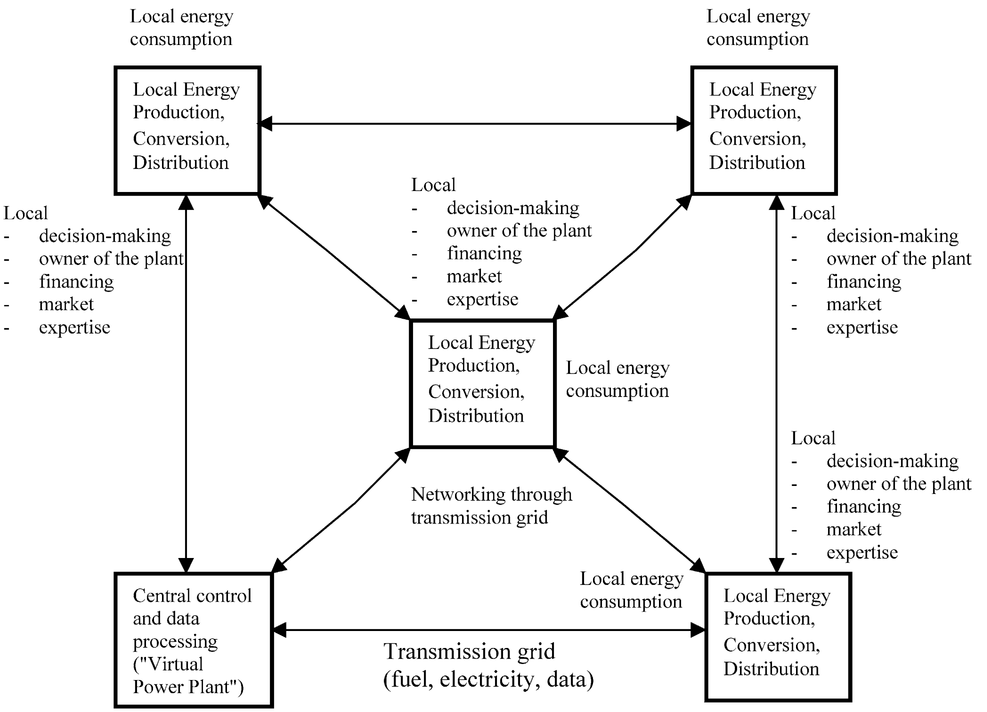

Fig. 4. An example of distributed regional system in an extended context.

of decentralization for each country and the reference cases, is transcribed on a scale of 1 (centralized) to 5 (decentralized) and illustrated by diagrams, as shown in Fig. 5.

The comparison shows that both Finland and Sweden are dependent on imported fuels. Another observation is that there are more power plants in Finland than in Sweden, and Finnish power plants are smaller. In addition, the total length of transmission lines and the number of power stations are smaller in the case of Finland. On the basis of these observations, the fuel supply system of both countries seems to be quite centralized. This probably will be the situation until fossil fuels are exhausted and the world is forced to start using other sources of energy. With respect to other aspects, there is no significant difference between Finland and Sweden. A slight trend towards distributed energy generation can be observed in Finland, however.

This comparison was presented for the sake of an example. Any detailed information about the energy system inside the country is not given. Only a small amount of technological indicators and statistical data is concerned. In addition, this example has been established according to a subjective opinion of the authors of this article. Thus, one should accept that it is quite general in nature. Premature, firm conclusions should be avoided. In a more detailed analysis a country should be considered region by region, while also finding out political, economic and social indicators by means of interviews and other field studies.

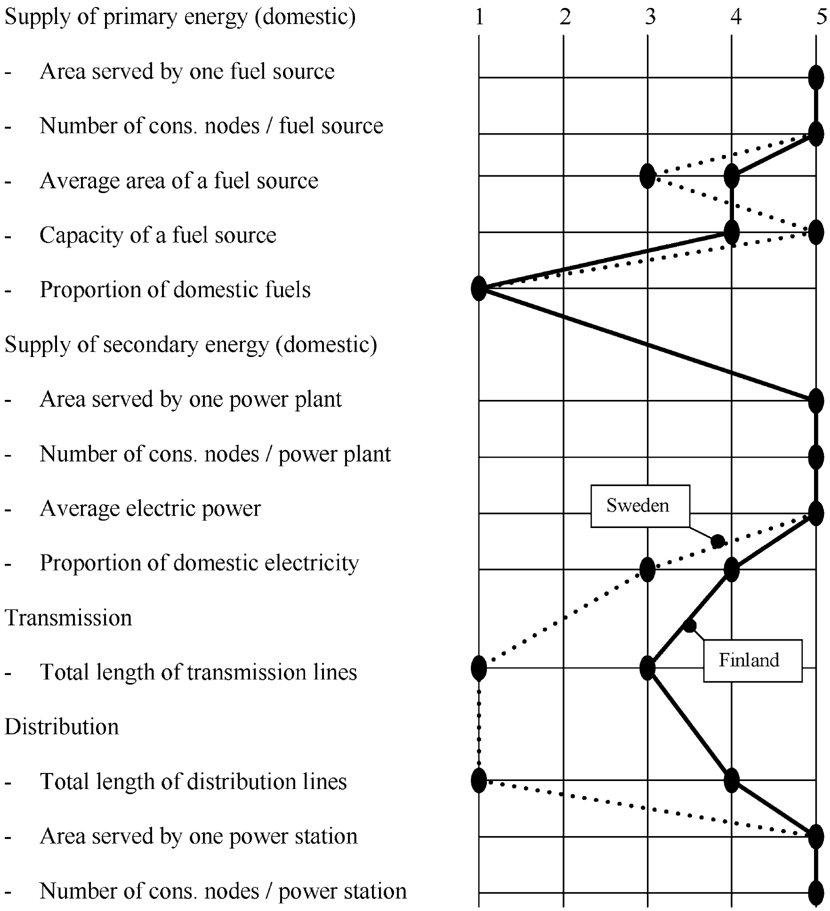

Fig. 5. Profile of the degree of decentralization in Sweden and Finland (1 = centralized reference case, 5 = decentralized reference case).

3. Distributed energy systems and sustainable development

3.1. What is a sustainable energy system?

In general, sustainability means an equitable distribution of limited resources and opportunities in the context of the economy, the society, and the environment [33] It aims at the well-being of everyone, now and in the future, admitting that needs in the future can be completely different than what can be imagined at the moment [34].

In the literature, a sustainable energy system has been commonly defined in terms of its energy efficiency, its reliability, and its environmental impacts. The basic requirements for an energy system are crystallized well by Bonser [35], as the ability of an energy system to 'generate enough power for everybody's needs at an affordable price' and to 'help supply the clean, safe and reliable electricity'.

On the other hand, the typical characteristics of a sustainable energy system can be derived from political definitions. The energy policy objectives are quite similar in industrialized countries [36,37]. Improving the efficiency of energy production and ensuring reliable energy supply seem to be common interests. Instead, the means to achieve these objectives vary slightly. In developing economies, more weight has been put on developing the infrastructure itself by means of basic measures like the improvement of nuclear safety and the reduction of environmental effects [38]. The typical characteristics of a sustainable energy system according to the national energy strategies for Finland, Lithuania, and the USA, are presented in Table 3.

Recently, one of the most popular subjects of discussion has been the security of the energy system. Countries directly exposed to the effects of September 11th 2001, seem to be especially eager to describe a sustainable energy system in terms of safety and security. Because the major part of the world's oil reserves is located in countries exposed to the risk of political conflicts, an energy system can be made less attractive to acts of terror by decreasing its dependence on oil (and other fossil fuels). Hence, regional co-operation and local choices should be encouraged to increase the use of local energy sources [38,39]. The improved use of local resources can be seen as the other side of safety and security in the context of a sustainable energy system.

Sustainable development does not make the world 'ready' for the future generations, but it establishes a basis on which the future world can be built. We regard a sustainable energy system as a cost-efficient, reliable, and environmentally friendly energy system that effectively utilizes local resources and networks. It is not 'slow and inert' like a conventional energy system, but it is flexible in terms of new techno-economic and political solutions. The introduction of new solutions is also actively promoted.

A sustainable energy system can be defined also by comparing the performance of different energy systems in terms of sustainability indicators. In principle, this comparison

Table 3
The characteristics of a sustainable energy system according to national energy strategies [36–38]

Finland	Lithuania	USA
Reliability of the energy sector	Reliable and safe energy supply at least cost	Energy security due to diversity of fuels
Efficient use of energy and energy-saving solutions	Enhanced energy efficiency	Economic efficiency due to competition and diversity of fuels
Competition and innovations in the energy market	Improved energy sector management and implementation of market economy principles	Development of energy technology by means of research and development and partnerships between public and private sectors
A versatile and cheap capacity for energy production	Reduced negative impact on the environment	Regulation and incentives to ensure public health, safety and consumers rights
Use of bioenergy and other domestic energy sources	Nuclear safety	
Support of advanced energy technology	Integration into the energy systems of the EU	
Decreased amount of carbon in the energy system	Regional co-operation and collaboration	

would be quite similar to the analysis presented in Section 2.3. The analysis is not of concern in this article, but Hecht [40] presents quite a versatile list of web-sites concerning sustainability indicators on the basis of which the comparison can be made. An interesting subject of research is also associated with the relation between sustainability indicators and the indicators of the degree of decentralization.

3.2. Sustainability of a distributed energy system

Distributed energy generation has become an object of interest quite recently Thus, the pros and cons of a distributed energy system have not been largely discussed. Instead, the feasibility of decentralization has been usually discussed in other contexts. The evaluation of decentralization can be based, for example, on the analogy between energy and information systems [41]. When the energy demand of a region is satisfied by a distributed energy system, the change of information between single units is essential to keep the system in balance. A distributed energy system can be regarded as an information system, and the characteristics of information systems are analogous to those of energy systems.

In terms of decision-making, expertise, and knowledge, a centralized system seems to be beneficial, because it facilitates finding information and results in a clear division of responsibility [42,43]. In contrast, the units of a centralized system are large and inflexible, and ‘all the eggs are put in one basket’. The situation is the opposite in the context of decentralized systems. The risks are diminished and a system can be made flexible, but information can be hard to find and there is no clear answer to the question of responsibility. A summary of benefits and drawbacks of centralization and decentralization in the context of information systems, is presented in Table 4.

The attributes flexibility, networking, and locality should be stressed when describing distributed energy systems in terms of sustainability. Scalability (or ‘modular flexibility’) is an issue that must be considered in the design of an energy system, because the energy consumption varies from one year to another, and the need to build a new power plant occurs every now and then. It is, in all likelihood, more feasible to integrate a lot of small, decentralized units into the total energy system than to build a large power plant. The feasibility of various energy system patterns should be compared in terms of scalability in further studies before firm conclusions can be made. A good example of the multi-faceted nature of this issue is associated with the decision to build a new nuclear power plant in Finland [44].

There are also other forms of flexibility in the context of energy systems. A distributed energy system consists of a variety of energy conversion technologies, thus being adaptable to a wide range of fuels. On the other hand, the diversity of technologies means a certain kind of ‘ flexibility in ticme’. When technology advances, obsolete units can be replaced by new ones with relative ease [5]. It is also possible that small energy conversion units would be transferred following internal migration streams in order to avoid building new power plants and fixed transmission capacity.

In this article, the term ‘networking’ especially refers to the ability of units of a distributed energy system to ‘live’ in a network. A unit can work independently, but an interaction between the nodes of a network is still established. This sort of structure is not very vulnerable to external risks like terrorist attacks and natural disasters.

Table 4
A summary of benefits and drawbacks of centralization and decentralization in the context of information systems [42,43]

Centralized		Distributed	
Benefits	Drawbacks	Benefits	Drawbacks
•Information easy to find	•Units must be large	•Scalability	•Fragmented information
•Responsibility, management and expertise easily placed	•Large by-investments	•Shared load	•Lack of uniformity and consistency
•Only a few educated persons needed	•'all the eggs in the same basket'	•Ability to 'live' in networks	•Considerable effort in management and education
•Uniformity	•Long distances between production and consumption	•Can work independently	
	•Cannot work independently	•Individuality	
	•Lack of individuality	•Flexibility	
	•Inflexibility	•Even distribution of political, technological, economic and social resources	
		•Increased control at the local level	
		•'Not all the eggs in the same basket'	

Accordingly, possible malfunctions can be easily located. All the previously mentioned factors make an energy system more reliable.

The third important aspect is locality, i.e. improved utilization of local resources in the context of energy systems. In terms of technology, distributed energy generation especially aims at the utilization of local fuels. In practice this refers to local fuel harvesting and storage. Distributed energy generation may also promote local business opportunities, and develop products and services based on local raw materials and labor.

Many benefits are associated with locality. Firstly, it means the absence of transmission lines, large power plants, and fuel storage, which spoil the landscape. The environmental load is also reduced due to the avoidance of additional energy required to compensate transmission losses. Secondly, new jobs can be created, improving local well-being. In addition, distributed energy generation provides even private real estate owners with an opportunity to receive income by selling surplus electricity. This may positively affect their energy consumption behavior, thus improving the efficient use of energy in the whole society.

The drawbacks of distributed energy generation can be seen simply as the 'other side of the coin'. Although distributed energy systems are flexible and work effectively in networks utilizing local resources, they are always more 'fragmented' than centralized systems. Thus, it is important to make the system work 'as a team'. Common standards and laws must be established as well as effective data-processing systems. Single units must be compatible

with each other and they must have a common information format. The required increase in the number of experts due to the fact that decisions are subordinated to local decision-makers can be seen as a drawback.

In terms of the environment, the superiority of distributed energy generation over centralized energy generation is not unambiguous either. Required new structures, such like gas lines or fuel stations can spoil the landscape. However, if global energy consumption remains unchanged and traditional fuels and technologies are still used, then the emissions remain constant and no improvement can be seen in the condition of the environment. Decentralization is likely to affect also the distribution of emissions, but this issue is not dealt with in this article.

As a conclusion, we cannot say that complete decentralization is a trend that should be encouraged. The best solution is likely to be an energy system that combines the benefits of both centralized and decentralized energy generation. A summary of pros and cons of a distributed energy system, is presented in Table 5.

3.3. The reliability of distributed and centralized energy systems

It is reasonable to dedicate a whole section to the reliability of an energy system, because it is one of the most important issues in the context of sustainability of energy systems Reliability can be regarded as the ability of an energy system to secure electricity supply at a reasonable price. It can be demonstrated by the way the energy systems react to problems in energy supply. Let us return to the cases of Finland and Sweden, analyzing two scenarios that commonly cause problems. In the first scenario, a unit loses its ability to work as a consequence of a natural disaster or a war. In the second scenario, the supply of imported energy is stanched. It is reasonable to assume that the malfunction of a unit principally affects every consumption node that the unit serves. The effect can occur directly in the form of disturbances in electricity networks or indirectly in the form of increased prices of electricity. In the worst case, a region may remain without electricity.

Because the use of domestic primary energy sources in the case of a centralized reference energy system is only 1% of total primary energy use, the shutdown of a single local primary energy source is not likely to cause major problems. Instead, if the import of primary energy is blocked, problems will occur also in the case of a decentralized reference energy system. The problems, however, are obviously much more tolerable than in the centralized case, in which the entire energy system is practically disabled.

Secondary energy supply seems to be dramatically affected by the shutdown of a power plant or a power station in both centralized and decentralized reference cases. In the centralized case, the shutdown of a power plant exposes almost 200,000 consumption nodes to problems. In practice, this number may be even greater, because we do not know exactly which power plant generates the electricity for a certain consumer. The compensation of this electricity shortage requires time and it has obvious effects on the economy. In the decentralized case the number of consumption nodes served by a power plant is less than 200. In the case of a shutdown, the effects are much more limited than in the centralized case. In addition, because of the absence of long transmission lines and the ability of a decentralized energy system to work in networks, the negative effect of the shutdown of one single power plant or power station can be reduced or even eliminated. In the reference case,

Table 5
A summary of pros and cons of a distributed energy system

Sector of sustainability	Benefits	Drawbacks
Flexibility	• scalability to changes in heat and electricity demand	• compatibility of the components required
	• open to new technologies	• life-cycle of single solutions is not necessarily long
	• flexibility for different fuels because of versatile technologies	• new laws and rules needed
	• adaptable to the "future of networks"	• unsure if common standards will be found
	• takes into account the changing individual needs via decentralized responsibility in decision-making	
Reliability	• not vulnerable to external risks	• may increase risk of hazards in consumption point due to extra devices
	• no wide electricity blackouts because of independency on electricity distribution	
Local and global well-being of humans	• improved employment possible	• some people may find increased responsibility as difficult and new technology as bizarre
	• new local market opportunities and competition	• "someone's bread can be another one's death"
	• gives a feeling of independence and self-control	
	• can "teach" private energy consumers	
Environment	• no deteriorated landscape due to large power plants and lines	• local distribution of emissions
	• decrease in emissions due to elimination of transmission losses	• effects of possible new fuel infrastructure (e.g. natural gas network)
Utilization of local resources and networks	• utilization of existing infrastructure	• may require changes in existing infrastructure at the beginning
	• more effective utilization of building sites	• increased need for education and training
	• utilization of local fuels	
	• utilization of information networks	

secondary energy supply is mainly based on domestic (regional) power plants. Thus, the interruption of imported secondary energy supply is not fatal either.

The previously mentioned scenarios illustrate a critical situation when the energy supply is seriously damaged. In many cases the changes are slower and more controlled, but they can still dramatically affect the continuity of energy supply. For example, strict limit values for emissions can be set by new environmental laws, making the use of new technology obligatory or even by forbidding the use of old technology. Sometimes the question is of political decisions, for example, whether to give up nuclear power. If the change is required on a strict schedule, the alternative technologies can be found easily in terms of distributed

energy generation. Although, changes are possible without extended shutdowns. The threshold to make changes to a small unit is likely to be lower.

Although fuel prices can change quickly as a consequence of wars or natural disasters, they can also change because of various other factors associated with the operational environment. In terms of centralized energy generation, however, the consumers strongly feel the effects of changes in fuel price, because the traditional energy producers commonly do hot have an opportunity to quickly start using cheaper fuels. On the contrary, distributed energy systems will be—or at least they should be—designed considering their flexibility in terms of fuels. Therefore, the consumer price of energy is not particularly sensitive to the changes in fuel price. Using various fuels may cause some additional costs, for example, in the form of reduced efficiency or extra service costs, but they are not of concern in this context.

4. Conclusions

The concept of a ‘distributed energy system’ refers to an energy system in which energy conversion units are located close to energy consumers In addition to the distribution of technology, a distributed energy system means the reallocation of decision-making, expertise, ownership, and responsibility in terms of energy supply. In practice, the energy system in the future is going to be a mixture of centralized and distributed sub-systems, operating parallel to each other. In this context, if an existing energy system already includes many decentralized sub-systems in a certain region, the region is likely to be favorable for the further development of distributed energy generation. If the most favorable regions can be recognized in this respect, energy utilities and product suppliers will become aware of the best market opportunities for distributed energy technology. In this article, we use the degree of decentralization as a means to evaluate regional energy systems. This analysis can also be applied when evaluating the vulnerability of an energy system.

The main characteristics of a sustainable energy system are (cost-) efficiency, reliability, and environmental-friendliness. Local resources and networks are utilized effectively and the introduction of new technoeconomic and political solutions is also actively promoted. The ability of distributed systems to rise to the challenge of sustainable development is mainly based on flexibility, locality, and networking. The flexibility of distributed energy systems is associated with their scalability and ability to utilize various energy conversion technologies and fuels. An improvement can be seen also in the reliability of energy supply because of the tendency of distributed systems not to ‘put all the eggs in one basket’. This is related to their ability to operate in networks and utilize local resources. In addition, distributed energy systems are environmental-friendly because of the absence of large power plants and transmission lines. When it comes to local decision-making and expertise, the ‘educative’ effect of distributed energy generation should not be underestimated. The drawbacks of distributed energy generation can be seen as the ‘other side of the coin’. They are mainly associated with the fact that distributed systems are ‘fragmented’. There are problems to be solved, linked to the questions of responsibility, the compatibility of single units, and also the lack of common standards and laws.

Our conclusion is that a distributed energy system is a good option with respect to sustainable development in the long run. In the future, our research will concentrate on

evaluating actual cases of on-site energy generation in the context of residential buildings. The competitiveness of a fuel-cell-based micro-CHP system will be dealt with by comparing it to the alternative solutions of residential energy supply in terms of life-cycle costs and environmental effects during a long period of time.

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